TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 881

A HOT-WIRE CIRCUIT WITH VERY SMALL TIME LAG

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SUMMARY

A circuit for a hot-wire anemometer for the measurement of fluctuating flow is presented in the present report. The principal elements of the circuit are a Wheatstone bridge, one branch of which is the hot wire; and an electronic amplifier and a current regulator for the bridge current which in combination maintain the bridge balance constant. Hence the hot wire is kept at practically constant resistance and temperature, and the time lag caused by thermal inertia of the wire is thereby reduced.

Through the addition of a nonlinear amplifying stage the reading of the instrument has been rendered proportional to the velocity.

A discussion of certain characteristics of the circuit and the results of related calibration tests are given.

INTRODUCTION

The circuit presented in the present report is the result of work conducted since January 1940 at Case School of Applied Science in connection with a research project sponsored by the National Advisory Committee for Aeronautics, at the Graduate School of Engineering of Harvard University where the basic idea was evolved in August 1940, and at the National Bureau of Standards where staff members of the Aerodynamics Section tested the circuit and suggested various improvements. Special acknowledgment is due Mr. Ernest R. Jervis of East Orange, N. J., who designed the original wiring circuit, suggested the use of the various electronic devices, and proposed solutions of numerous electrical problems. An improvement of the original circuit designated circuit I was designed and tested by Mr. A. R. Kantrowitz of the NACA and is included in the report as circuit II. Mr. Kantrowitz also suggested the method discussed hereinafter for calibrating the bridge for alternating-current unbalance

THE CIRCUIT

The hot-wire circuit consists of the following principal elements:

(a) a Wheatstone bridge, one branch of which is formed by the hot wire

(b) a regulating circuit for the bridge current including a battery and one electronic valve

(c) an electronic direct-alternating-current amplifier operated by slight variations of the unbalance of the bridge and controlling the current regulator

Three forms of the circuit, which appear to have certain merits and are therefore presented herewith, were evolved in the course of the development.

Circuit I (fig. 1) was found to operate satisfactorily at frequencies below 2000 cycles; at higher frequencies, the compensating action is impaired by the capacitances of batteries B_3 and B_4 with respect to ground, which produce shunting of the plate resistances R5 and R6, respectively.

In circuit II (fig. 2), the shunting capacitances have been reduced and the response of the instrument has been thereby extended to higher frequencies, although this condition increased the number of batteries required.

In the basic circuit III (fig. 3), small neon tubes (reference 1) are used to couple successive amplifier stages. This circuit is simpler than circuits I and II.

The basic circuit III, or any of the basic circuits, may be provided with an additional amplifier stage, also shown in figure 3, and through this combination it is possible to obtain readings proportional to the wind velocity past the hot wire. This proportional characteristic is obtained by operating certain electronic tubes which have been found suitable for the purpose in the nonlinear range of its characteristic. The additional stage is therefore referred to as the "nonlinear amplifier stage."

The circuit constants are given for circuits I, II, and III in table I.

PRINCIPLE OF OPERATION

If certain dynamic effects discussed later are neglected, the operation of the basic circuit can be explained as follows: The circuit is assumed to be operating at a given condition of equilibrium. Then a disturbance, such as may be produced by a change of velocity past the hot wire occurs, causing a variation of resistance of the hot wire and consequently a variation of potential between points (2) and (4) of the bridge (fig. 1). This electric impulse is transmitted and amplified by the amplifier stages. A variation of the potential between grid and cathode of the current-regulating tubes and a corresponding variation of the hot-wire current is the result. The resistance of the hot wire is thereby varied in such a way as to counteract the original disturbance, and a new condition of equilibrium is established. By proper choice of the amplification ratio of the amplifier it is possible, within certain limits imposed by tube characteristics and stability of the circuit, to make the difference between the hot-wire resistance of the original and the new position of equilibrium very small.

In addition to the reduction of fluctuation of hot-wire resistance, there is a corresponding reduction of the time lag of response to variation of the condition of operation, provided the effect of capacitances in the circuit is also kept small. This provision is necessary because the magnitude of the time lag depends both upon the residual thermal inertia of the wire and upon the effect of such capacitances.

Hot-wire readings with this circuit are obtained by measuring directly the heating current or by measuring a quantity proportional to it, such as the grid voltage of the current-regulator tubes with respect to the ground.

In order to obtain a reading linear with velocity, use is made of an additional amplifier stage operated in a range of its characteristic, in which the exponent of the variation of plate current with grid potential, expressed in exponential form, is equal to the reciprocal of the exponent relating variations of heating current and of velocity past the hot wire. Tubes, such as those listed in table III, were found to have a suitable range in which stable operation may be obtained. When adjusted for linearity between reading and velocity, the circuit may be expected to measure the mean velocity of fluctuating rectilinear flow.

If, instead of mean velocities, mean rates of momentum of fluctuating rectilinear flow are to be measured, a nonlinear amplifying stage adjusted to give a reading proportional to the square of the velocity may be expected to give the desired readings.

CHARACTERISTICS OF OPERATION AND CALIBRATION TESTS

Variation of Heating Current with Velocity

If constant resistance of the hot wire, or zero rate of increase of heat energy in the wire $\frac{dH}{dt} = 0$ is assumed, the balance of energies supplied to and dissipated by the hot wire may be expressed by King's equation (references 2 and 3).

$$i^2 = \frac{T - T_o}{R} (k + C \sqrt{V}) \qquad (1)$$

where

i instantaneous heating current

R resistance of wire (maintained constant)

T temperature of wire (maintained constant)

T_o air temperature

V instantaneous wind velocity

$k(T-T_o)$ rate of heat loss from wire by radiation and free convection

$C \sqrt{V}(T-T_o)$ rate of heat loss from wire by forced convection of air stream at speed V

A circuit, shown in figure 1, was calibrated by measuring the heating current over a certain range of air velocities. Several runs were made with various heating currents i_o at zero speed. The hot wire used in these tests was a tungsten wire 8.6 microns in diameter and 5 millimeters long.

The results are shown in figure 4, in which the square of the heating current i^2 has been plotted against the square root of the velocity $\sqrt{V}$. These experimental data are in qualitative agreement with equation (1). The operation of the circuit was stable throughout the range tested.

Over-All Transconductance of the Circuit

Response of the circuit to variations of velocity and to fluctuating velocity may be analyzed by investigating the over-all transconductance of the circuit.

The over-all transconductance g_m is defined as the ratio of variation of heat current of the wire i to variation of unbalance of the bridge e.

$$g_m = \frac{\partial i}{\partial e}$$

Since the branch on the bridge parallel to that containing the hot wire has a resistance approximately 100 times that of the hot wire, the bridge current may be considered equal to the heating current of the wire without incurring an appreciable error.

The over-all transconductance is given by the equation

$$g_m = \mu_1 \mu_2 g_{m_3} \frac{r_{b_1} r_{b_2}}{r_{p_1} r_{p_2}} \frac{k_1 k_2}{(1-\mu_1'\beta_1)(1-\mu_2'\beta_2)} \tag{2}$$

where

g_m over-all transconductance

g_{m_3} transconductance, 3d or current-regulator stage

μ amplification ratio

r_b load resistance

r_p plate resistance

k ratio of stage amplification with neon-tube-coupling loss to stage amplification with zero-coupling loss (K is defined later)

μ' effective stage-amplification ratio

β feedback factor

Subscripts $_{1,2}$, ... refer to 1st, 2d, ... stage, respectively.

The investigation has been carried out for a basic circuit, shown in figure 3. It is applicable generically, however, to the other two circuits as well.

In analyzing the over-all transconductance the following effects, which will be discussed in detail, have been considered:

(a) The coupling loss through the neon-tube coupling

(b) The loss of amplification from the potential difference across the resistance r_3 of the bridge

(c) The effect of alternating-current unbalance of the bridge

(d) The effect of direct-current unbalance of the bridge

(e) The effect of interelectrode capacitances

<u>Coupling loss through neon-tube coupling</u>.- It can be shown that the coupling loss through neon-tube coupling (fig. 5(a)) may be expressed through the factor

$$k = \frac{1}{1 + \frac{r_b}{r_l}} \tag{3}$$

This loss may be kept small by choosing the grid-leak resistance r_1 large as compared with the load resistance r_b of the previous stage. With the data for circuit III (fig. 3), this factor has a value of $k = 0.89$ for the first amplifier stage.

In order to provide against instability that might originate in the neon tube, an additional resistance r_7 and r_{14} for the first and second stage, respectively (fig. 3), may be inserted to produce a voltage-divider effect.

<u>The loss of amplification from the potential difference across the resistance r_3 of the bridge</u>.- It is seen that as the bridge current i increases due to an increase of grid voltage of the current-regulator stage e_{g_3} (fig. 5(b)), point 4 of the bridge becomes more negative with respect to point 1, and consequently there is a corresponding decrease of the voltage e_{g_3}. If

$$i' \approx i$$

and if the effective transconductance, defined by

$$g_{m_3}' = \frac{g_{m_3}}{1 - \mu_3' \beta_3} = \frac{\partial i}{\partial e_{g_3}}$$

where

$$g_{m_3} = \frac{\partial i}{\partial \Delta e_{5,4}} \quad \text{and} \quad e_{g_3} = \Delta e_{5,4} - r_3 i$$

is introduced, then

$$g_{m_3}' = \frac{g_{m_3}}{1 + r_3 g_{m_3}}$$

and the feedback factor for the current-regulator stage is

$$\frac{1}{1 - \mu_3' \beta_3} = \frac{1}{1 + r_3 g_{m_3}}$$

For the circuit constants of circuit III,

$$r = 30 \text{ ohms}$$

$$g_{m_3} = 7000 \text{ micromhos for one tube and}$$

$$14{,}000 \text{ micromhos for two tubes}$$

it has the value

$$\frac{1}{1+r_3\, g_{m_3}} = 0.826 \text{ and } 0.705, \text{ respectively.}$$

The effect of alternating-current unbalance of the bridge.- Alternating-current unbalance may be caused by inductances or capacitances in the individual branches of the bridge. In general, their value can be kept low by appropriate design, except for the capacitance of the shielded hot-wire leads, the length of which depends upon the distance between the hot wire and the instrument. Their capacitance is of the nature of a distributed capacitance. In certain cases it may be compensated for by placing the resistance r_3 on leads of the same kind and of equal length as the hot-wire leads, provided that this arrangement does not affect the feedback of the current-regulator stage discussed in the preceding section. The effect of capacitances or inductances in the four branches of the bridge may be taken into account through a reduced capacitance C_{red} parallel to the hot wire, since it will be seen that the residual thermal inertia of the hot wire may be treated like an electrical capacitance in computing the circuit. It appears possible to compensate for the reduced capacitance by a variable condenser. If this condenser is placed parallel to r_2, its capacitance need not be large and it is possible to use an air condenser. Locating the compensating condenser parallel to r_2 appears to be preferable to its alternative position parallel to r_3 because in the former case it will not affect the feedback of the current-regulator stage.

Any residual reduced capacitance causes a feedback that is given by

$$\mu'\beta = \frac{R\left(j\omega C_{red} + \frac{1}{R}\right) - 1}{r_3\left(j\omega C_{red} + \frac{1}{R}\right) + 1}\,(r_3 + R)\, g_m' \qquad (4)$$

This feedback, if negative, results in larger phase lag, if positive, tends to decrease the phase lag, as shown qualitatively by curves b and c, respectively, of figure 6. This feature may be used to calibrate and compensate the bridge for alternating-current unbalance.

<u>The effect of direct-current unbalance of the bridge</u>.- For the purpose of determining the effect of direct-current unbalance of the bridge, the variation of the hot-wire resistance with heating current is disregarded and the bridge is assumed to be unbalanced by the amount Δr (fig. 5(c)).

A current i'' then produces a potential

$$e_g = \Delta r \, i''$$

on the grid of the first amplifier stage. The same current produces, between points 1 and 3 of the bridge, the potential

$$e_o = i''(r_1 + r_2)$$

The ratio of these two potentials is

$$\beta = \frac{e_g}{e_o} = \frac{\Delta r}{r_1 + r_2}$$

This ratio leads to a feedback factor

$$\beta\mu' = \Delta r \frac{(r_3 + R)}{r_1 + r_2} g_m' \tag{5}$$

Through variation of unbalance of the bridge it is possible to produce regenerative, degenerative, or zero feedback by making $1 - \Delta r \dfrac{(r_3 + R)}{r_1 + r_2} g_m'$, respectively, larger than, smaller than, or equal to unity.

In the case of regenerative feedback $\left(1 - \Delta r \dfrac{r_3 + R}{r_1 + r_2} g_m'\right) < 1$, oscillations resembling relaxation oscillations arise in the circuit. As the amplitude of these oscillations exceeds a certain value, the bridge current is observed to vanish to zero. With regenerative feedback due to bridge unbalance, the circuit was found to be too unstable to use. Stable operation is possible for a limited range of degenerative feedback for which $\left(1 - \Delta r \frac{r_3 + R}{r_1 + r_2} g_m'\right) > 1$.

Although it appears possible that the circuit may be operated at zero feedback $\Delta r = 0$, tests have shown that at this condition it is excessively sensitive to outside disturbances. The amount of negative feedback affects the over-all transconductance of the circuit and the ratio of transconductance at zero feedback to transconductance with feedback is $\dfrac{1}{1 - \Delta r \dfrac{r_3 + R}{r_1 + r_2} g_m'}$. Measurements of this effect were made at the National Bureau of Standards and curves of the type of figure 5(d) were obtained. From experience with the instrument, the technique was developed of operating the instrument at a bridge unbalance $\Delta e = -2$ millivolts which remained essentially constant at all conditions of normal operation.

As the unbalance of the bridge was increased toward the regenerative side, the circuit would perform high-frequency oscillations of a large amplitude.

The effect of interelectrode capacitances.- If response to high-frequency velocity fluctuations is desired, it is necessary to keep all capacitances at a low value. These low values may be attained to some extent through proper design of the circuit. The effect of interelectrode capacitance of the tubes, however, unless compensated by special circuits, places certain limitations upon the magnitude of the load resistances of the amplifier, as can be seen from the following calculation:

Interelectrode capacitances of the first amplifier stage of circuit III (IN5 tubes)

Output	=	10 micromicrofarads
Input, 2d stage	=	3 micromicrofarads
Total	=	13 micromicrofarads

Load resistance r_{b_1} = 0.25 megohms

Assume 10,000 cycles $\frac{1}{\omega C}$ = 0.815 megohms

Ratio of amplification $$\frac{\frac{1}{0.25}}{\sqrt{\left(\frac{1}{0.25}\right)^2 + \left(\frac{1}{0.815}\right)^2}} = 0.915$$

Phase lag = 17°

Over-all transconductance.- The value of the over-all transconductance of circuit III for variations of zero frequency and neglecting feedback from bridge unbalance was computed as follows:

	1st stage	2d stage	[a]3d stage
Transconductance, μhos	480	480	2×7000
Load resistance, megohms	0.25	0.25	
Grid-leak resistance, megohms	2.5	1.5	
Grid-leak loss	0.91	0.86	
Amplification ratio	109.2	103.2	
Feedback factor			0.705
Over-all transconductance at zero frequency, mhos		112	

[a]Current-regulator stage.

This computed value agrees very well with the measured value. Characteristics at higher frequencies are discussed in a later section.

The Time Constant

For constant-resistance operation, the heating current varies as follows:

$$i = i_o(1 - g_m'(R - \overline{R})) \qquad (6)$$

where

i_o heating current at zero air velocity

$\overline{R}$ resistance of heated wire at zero velocity

R instantaneous resistance of hot wire

g_m' transconductance of circuit

The time constant for constant-resistance operation is given by Dryden (reference 3) as

$$M = \frac{4.2\ m\ s(\overline{R} - R_a)}{i^2\ R_a\ R_o\ \alpha}\ \frac{1}{1 + \dfrac{g_m'(\overline{R} - R_a)\overline{R}}{R_a}} \tag{7}$$

where

m mass of hot wire

s specific heat of metal of hot wire

R_a resistance of hot wire at temperature of ambient air

R_o resistance of hot wire at zero temperature

α temperature coefficient of resistivity

for values of the transconductance attainable with the compensating circuit

$$2g_m'\ \frac{(\overline{R} - R_a)\ \overline{R}}{R_a} >> 1 \tag{8}$$

hence equation (7) may be simplified to read

$$M = \frac{4.2\ m\ s}{2i^2\ g_m'\ \overline{R}\ R_o\ \alpha} \tag{9}$$

The time lag may be computed from values for the quantities appearing in equation (9) chosen in accordance with hot-wire technique as follows:

Material of hot wire	nickel
Mass density of wire, ρ, grams per cubic centimeter	8.85
Length of wire, l, centimeter	0.635
Diameter of wire, d, microns	12.7
Specific heat, s, calorie per $^{\circ}$C	0.1032

Heating current, i_o, ampere 0.05

Transconductance of circuit, g_m', mhos 100

Resistivity, r, microhms at 20° C 7.8

Temperature of wire, $\overline{T}$, °C 215

Temperature coefficient of resistivity, α . . . 0.00537

Time constant, M, second . . . . 42×10^{-6}

Effect of Time Constant upon Amplification

and Phase Lag

The time constant decreases the amplitude and causes a phase lag of the electrical impulse as compared with the true signal corresponding to the velocity fluctuation (reference 4).

The ratio of amplitudes at frequency $n = \frac{\omega}{2\pi}$ and at zero frequency is

$$\frac{1}{\sqrt{1 + M^2 \omega^2}} \tag{10}$$

and the phase lag is given by

$$\tan^{-1} (M \omega) \tag{11}$$

Numerical values for the decrease of amplitude and the phase lag computed for circuit III are as follows:

Assume $n = 5000$ cycles, then $\omega = 31,400$

For $M = 42 \times 10^{-6}$ sec:

Ratio of amplitudes = 0.61

Phase lag = 42.5°

The results of calibration tests of these quantities are given in figure 6 for the decrease of amplitude of response for the phase lag. These results were obtained for frequencies up to 8000 cycles, which was the highest that could be produced with the harmonic-wave generator. The signal was imposed upon the circuit across points 1 and 3 of the bridge. Phase lag was measured by impressing the signal upon the sweep circuit and the grid voltage of the current-regulator stage upon the ordinate of a cathode-ray oscillograph.

Further calibration tests of response over a range of frequencies were conducted in which the signal was produced aerodynamically instead of electrically. The apparatus used for this purpose (see figs. 7 and 8) was developed for the calibration of hot wires in fluctuating flow of large amplitude. It makes use of the directional characteristics of the wire.

In this device, the hot wire is mounted on a shaft, which may be rotated throughout a wide range of speeds, and placed into an air stream. The amplitude of the fluctuations produced as the wire rotates in the air stream may be varied from 0 to nearly 100 percent of the velocity of the air through increase of the angle subtended by the axes of the air jet and the rotating shaft from 0° to 90°.

The oscillograph records (fig. 9) were obtained with the calibrating device previously described. They were recorded with a General Electric oscillograph, after amplification of the output signal of the hot-wire instrument in a special current amplifier. The hot wire was a tungsten wire 8.6 microns in diameter and 1/4 inch long. Its axis of rotation, which is at right angles to the axis of the wire, was placed normal to the air jet.

The frequencies recorded on figure 9 range from 0 to 480 cycles per second and 540 cycles per second, respectively. In both cases the instrument begins to respond at approximately 40 cycles per second. No measurable decrease of amplitude of the fluctuations occurs between this threshold frequency and the maximum frequency recorded. Extension of the tests to higher frequencies was impossible because of limitations of the speed of the motor driving the hot wire, whose maximum speed was approximately 18,000 rpm. The fluctuations recorded at zero speed of rotation of the hot wire are due principally to the turbulence in the air stream and possibly in part to microphonic effects.

It is believed that the lower limit of response is not caused by the hot-wire circuit, which inherently responds to variations of zero frequency, but rather by the apparatus used for amplifying and recording.

Stability, Microphonic, and Thermionic Sensitivity

At very large amplifications of the output signal of the circuit, with the hot wire placed in a small confined space of air to reduce convection, an oscillation of a frequency of approximately 1800 cycles could be observed. This oscillation appears superimposed upon the impressed oscillations of from 40 to 150 cycles but is not apparent at higher frequencies. The origin of this frequency is traced to the feedback feature of the compensating circuit.

The amplitude of this oscillation in many cases does not exceed a few percent of the amplitude to be measured; furthermore, it may be reduced by adjustment of the bridge balance. It appears to become smaller as the resistance of the hot wire is increased. Further investigation into the nature and causes of this oscillation are contemplated.

Investigations at the National Bureau of Standards had disclosed that the instrument possessed a pronounced microphonic response arising in the tubes of the amplifier and also in the nonlinear amplifier stage. While no measurements have been made yet of its magnitude, this sensitivity has been reduced greatly by cushioning the amplifier tubes. Further reductions are believed possible by selecting from commercial tubes of the type used those of lowest sensitivity; by replacing the tubes used at the present time with types having the directly heated cathode but sturdier construction of the grid; by using tubes with indirectly heated cathode; or by substituting special tubes available with specified low microphonic sensitivity, such as are manufactured by the Western Electric Company. Information available for the special tubes with specified low microphonic sensitivity also includes ratings for thermionic sensitivity, and it is noted that for tubes of lowest microphonic response the thermionic sensitivity is only a small fraction of that for the other types mentioned.

Calibration of Linearity of the Instrument

Shown in Figure 3

It was found that the exponent by which the reading is related to the velocity can be adjusted readily to unity by varying the bias of the nonlinear amplifying stage. The exponent was found to be constant over a sufficiently wide range of velocities. Results of a calibration test are given in figure 10.

Directional Calibration of the

Directional Characteristics

Hot-wire readings of the instrument with linear characteristic taken at constant velocity but varying angle of incidence between direction of flow and hot wire are plotted in figure 11. The figure also shows in dot-and-dash lines the sin curve, and it is seen that the calibration curve (fig. 11) displaced a few degrees follows this sin curve with reasonable approximation, except in the range from 0° to 6° angle of incidence. It can be stated that the hot-wire instrument measures the component of velocity in the transverse plane of the wire. This characteristic of the hot-wire instrument may be used for determination of the velocity vector from readings with hot wires placed approximately at right angles to each other. Furthermore, simultaneous measurement with two hot wires may be adapted to the direct determination of the instantaneous and mean rate of momentum of flow of fluctuating velocity and direction.

CONCLUSIONS

Compensating circuits for operation of the hot wire at essentially constant resistance were found to respond to fluctuations of velocity over a wide range of frequencies including aperiodic changes of velocities.

Inasmuch as constant-resistance operation established a definite relation between heating current and wind velocity, it is possible through the addition of a nonlinear amplifier stage to obtain a linear relationship between instrument reading and wind velocity.

Quantitative investigation shows that response and phase lag are still affected by the residual thermal inertia of the wire and by capacitances in the circuit, and that this effect may not be neglected at high frequencies. There is, furthermore, a tendency to oscillations from instability and a sensitivity to microphonic disturbances. Investigation of the circuit characteristics appears to show, however, that these effects may be reduced by conventional technique.

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Cleveland, Ohio, April 1942.

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TABLE I - CIRCUIT CONSTANTS

Constant	Circuit I	Circuit II	Circuit III
T_1	IN5GT	[a]6C8G	IN5GT
T_2	IN5GT	[a]6C8G	IN5GT
T_3	6Y6G	6Y6	ISA6GT or 6B7
T_4		6J7	6Y6G
G			-12.5 to 12.5 μa;5000 ohms
C_2		25 micromicrofarads	
(Microamperes)			
A_1	0 to 200		0 to 200
A_2			0 to 100
(Volts)			
B_1	1.5		135
B_2	1.5		1.5
B_3	90		90
B_4	90		90
B_5	90		90
B_6	1.5		1.5
B_7	90		1.5
B_8	135		54
B_9	6		1.5
B_{10}			6
(Ohms)			
$R_1 + R_2$	2,500		5,000
R_3	30		30
R_4	10,000		10,000
R_5	[b].5		[b].25
R_6	[b].1		60,000
R_7	50,000		[b]2.5
R_8	75		[b].25
R_9	150		60,000
R_{10}			750,000
R_{11}			750,000
R_{12}			10,000
R_{13}			[b].15
R_{14}			50,000
R_{15}			25,000
R_{16}			75
R_{17}			150

[a]In one shell.

[b]Measured in megohms.

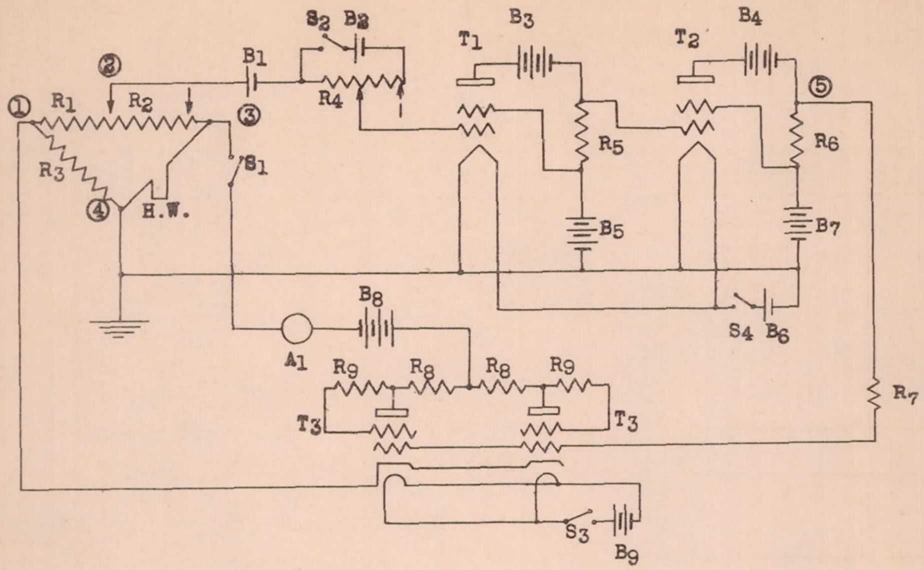


Figure 1.- Hot-wire circuit I.

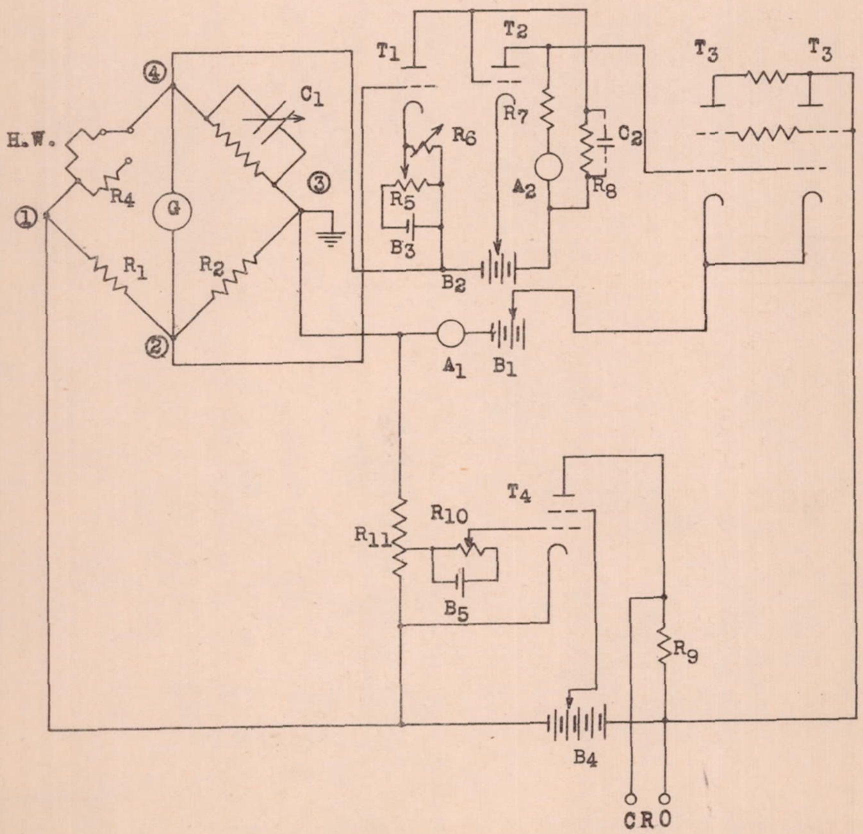


Figure 2.- Hot-wire circuit II.

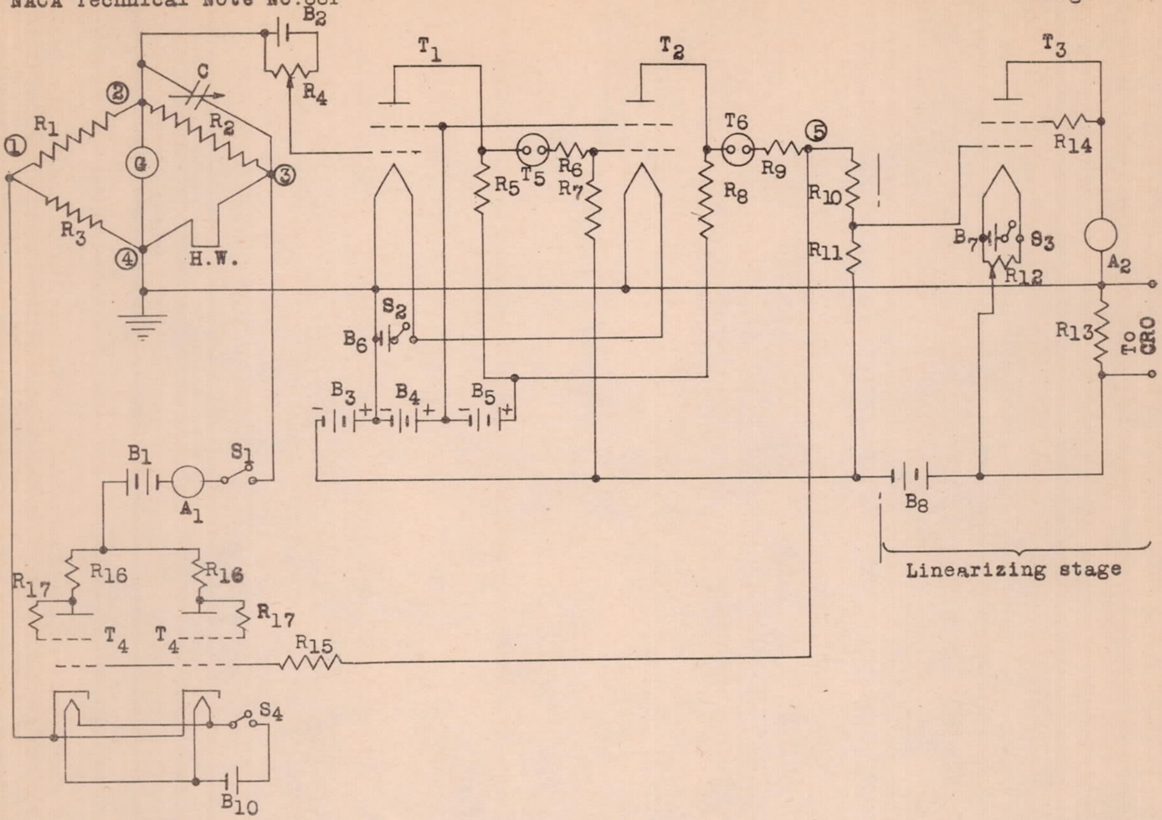


Figure 3.- Hot-wire circuit III with additional stage for linear reading.

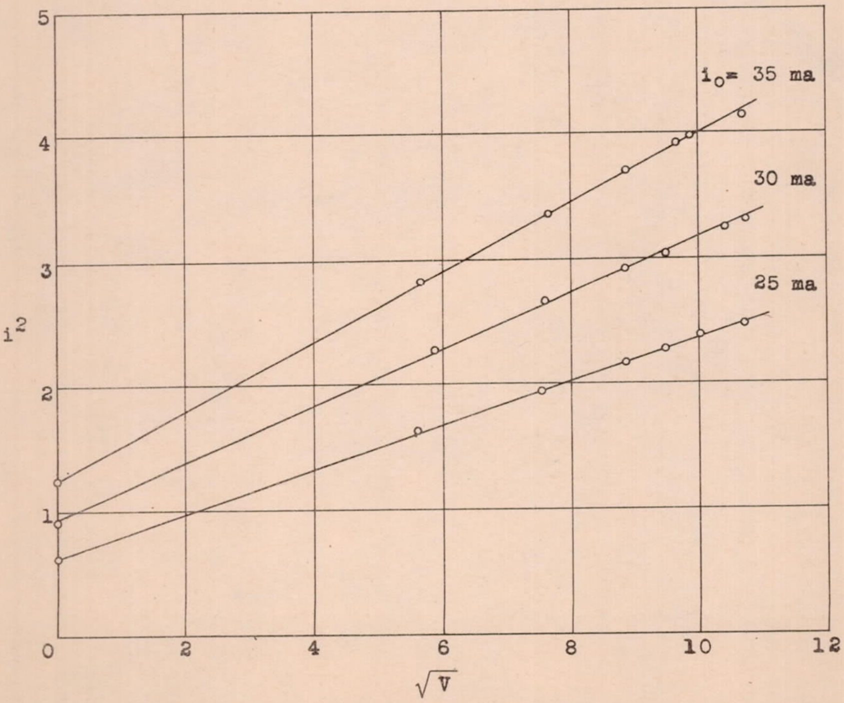
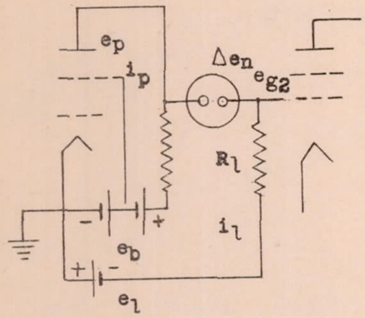
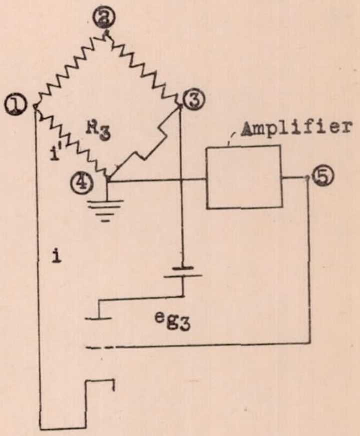


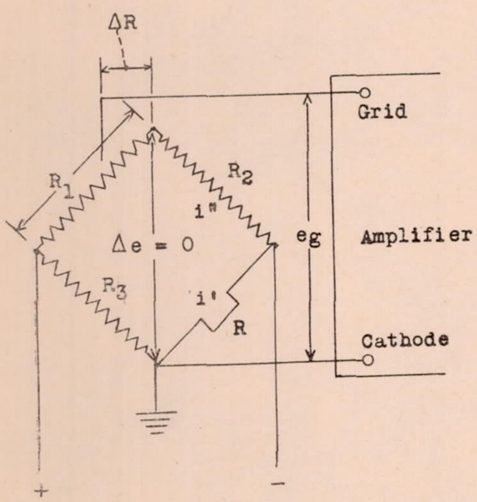
Figure 4.- Variation of heating current with velocity and wire temperature.



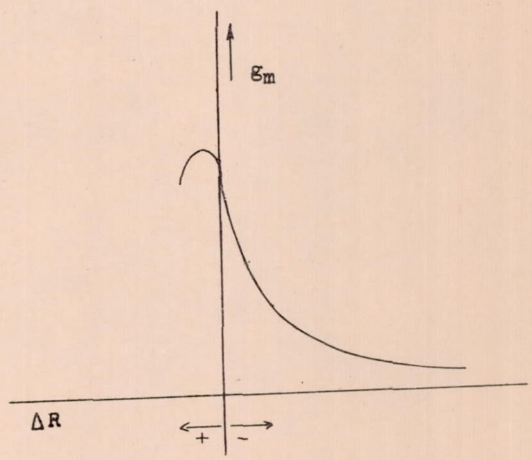
(a) Neon-tube coupling of the amplifier of circuit III.



(b) Effect of the potential across the bridge resistance R_3 upon the grid voltage of the current regulator stage.



(c) Effect of direct-current unbalance of the bridge.



(d) Variation of transconductance of the circuit with the direct-current unbalance of the bridge.

Figure 5.- Details of the hot-wire circuit.

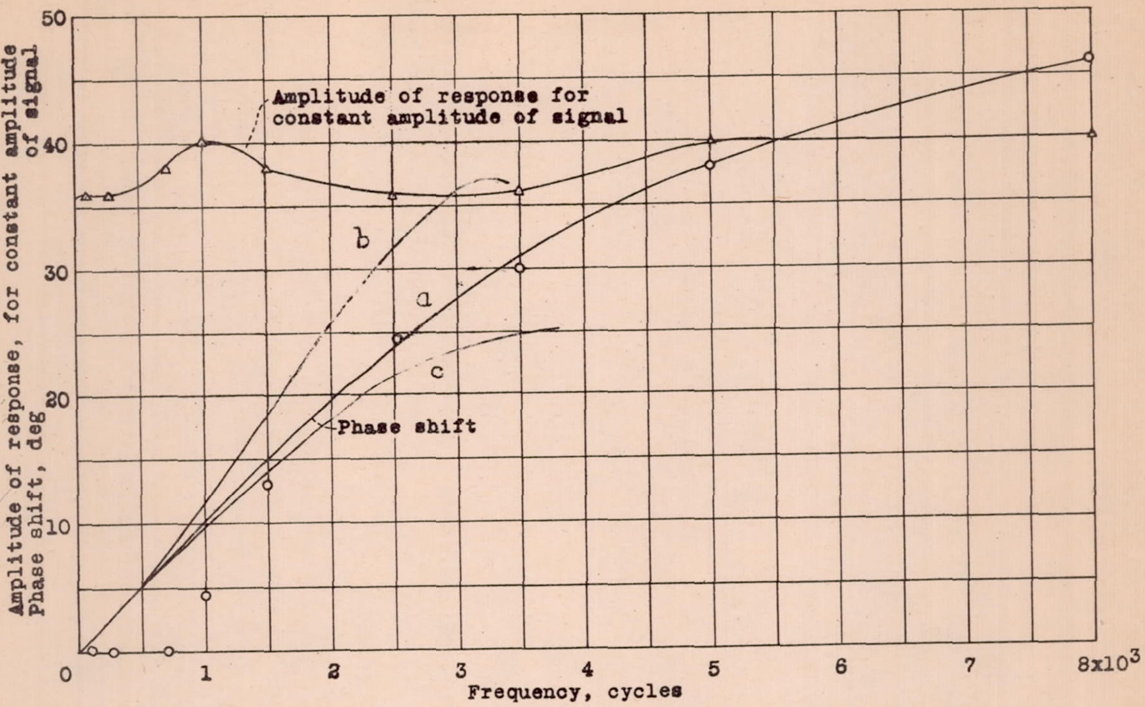


Figure 6.- Variation of amplitutde of response and of phase lag with frequency for circuit III.

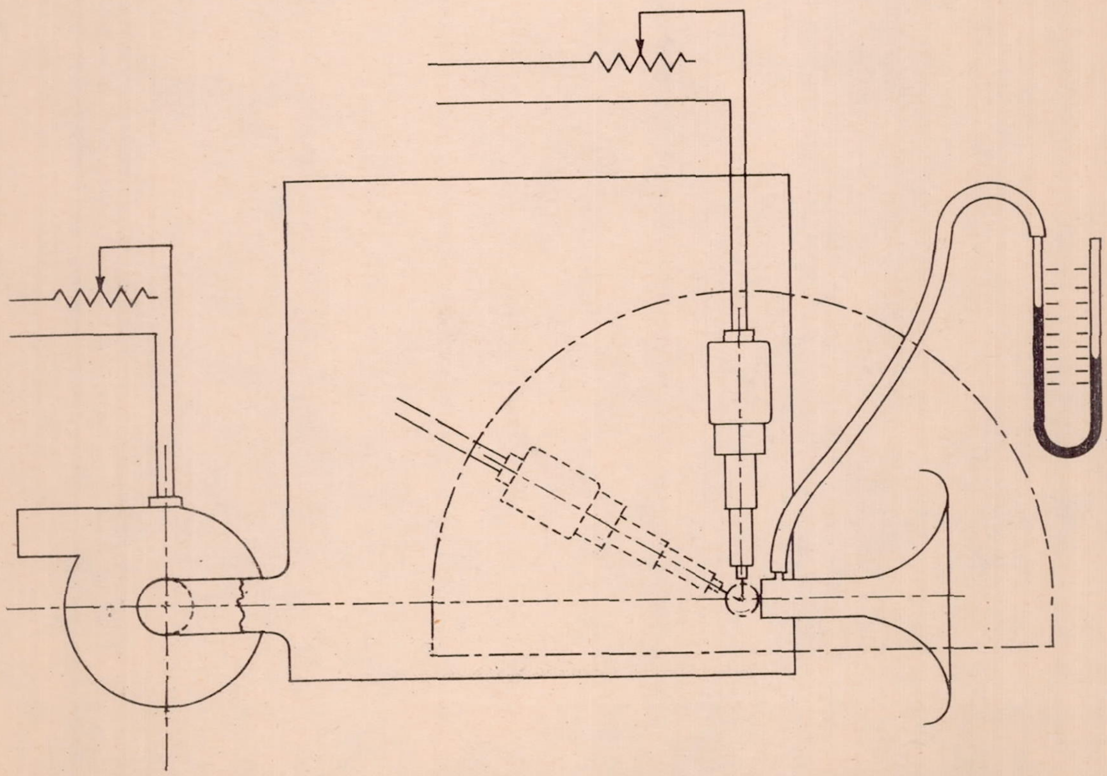


Figure 7.- Schematic drawing of the calibrating device for large amplitudes using the directional characteristics of the wire.

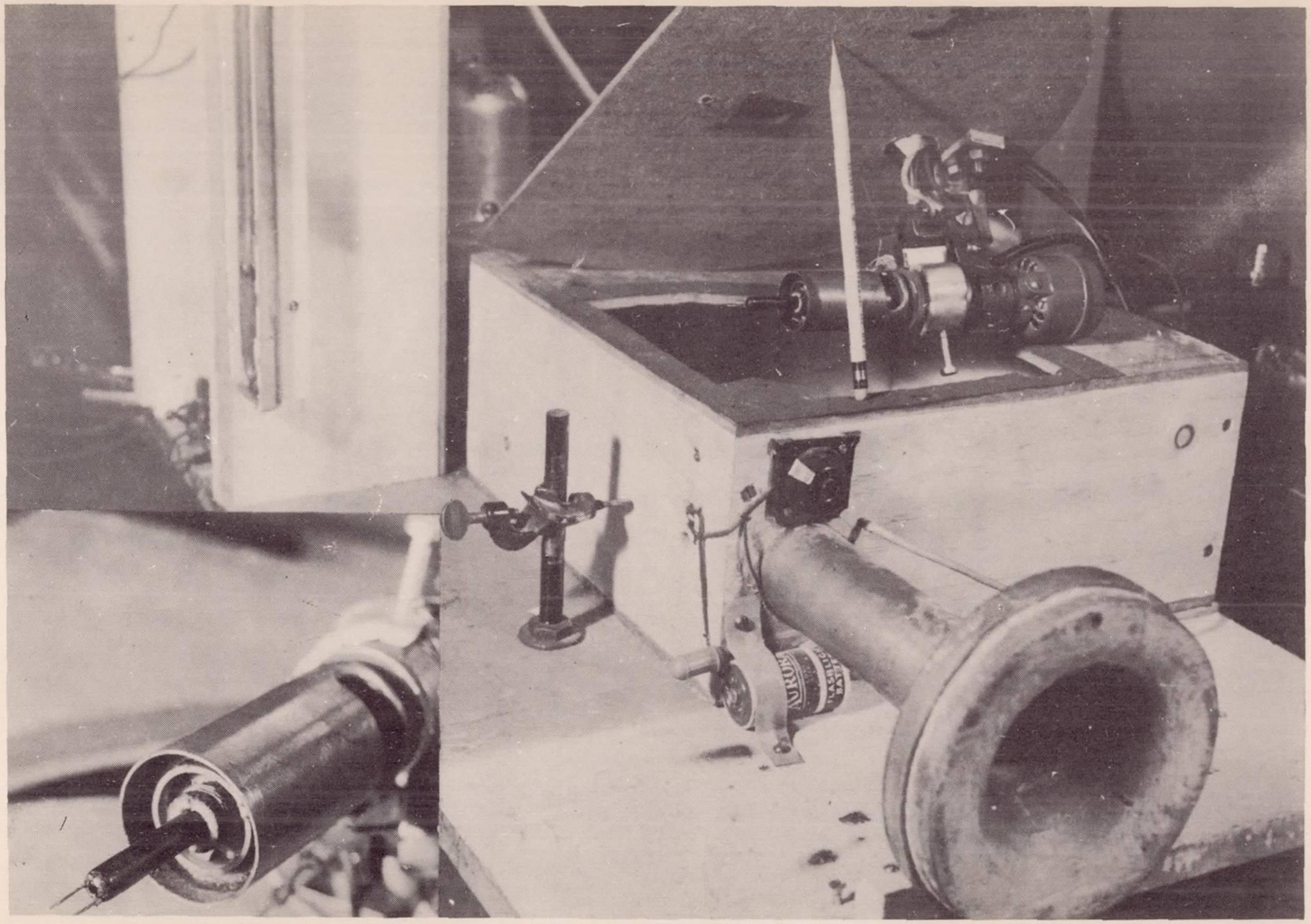


Figure 8.- Photograph of the calibrating device showing the hot-wire holder and sliding contacts in the insert to the left.

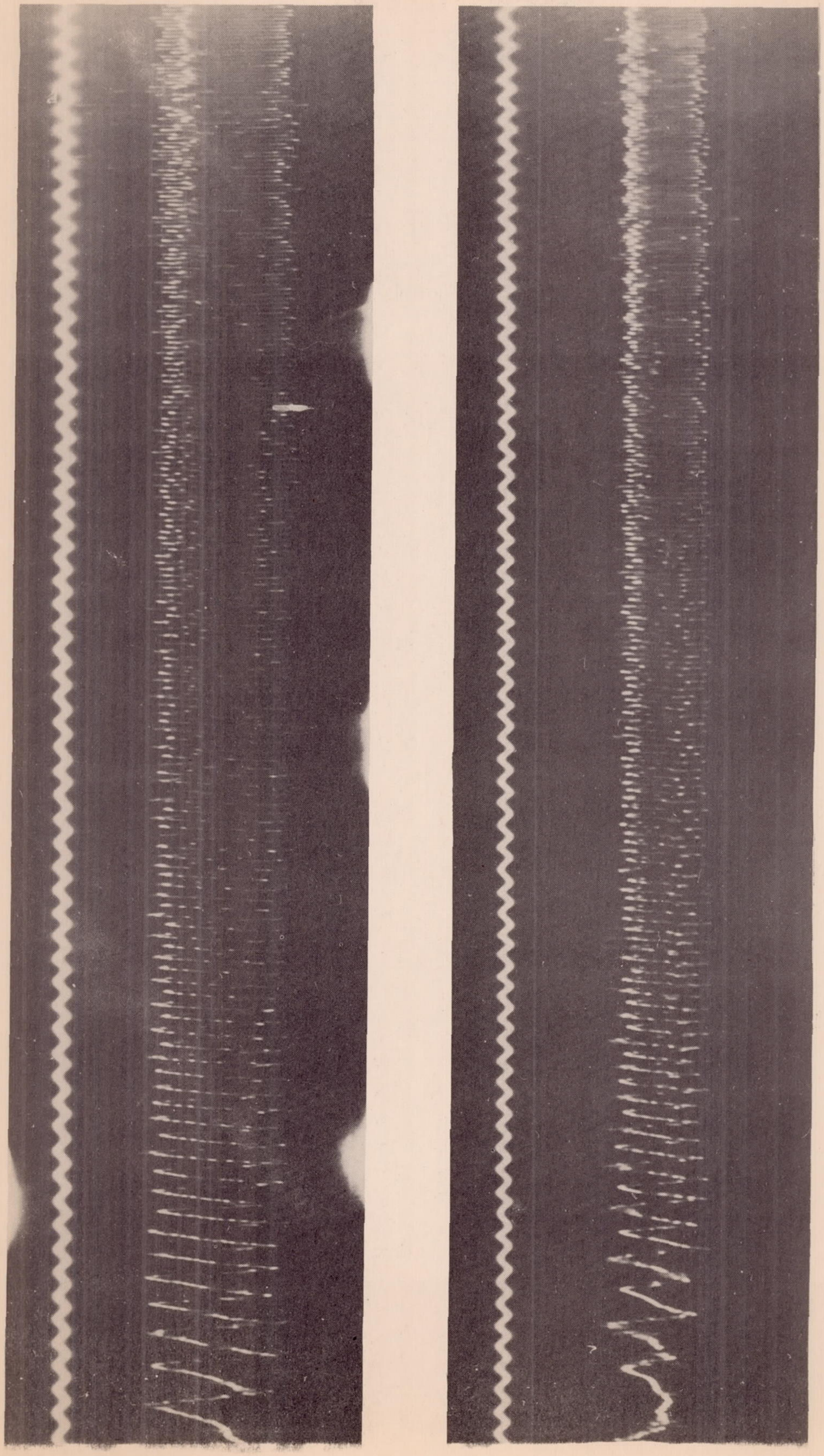


Figure 9.- Oscillograph record of the dynamic calibration test.

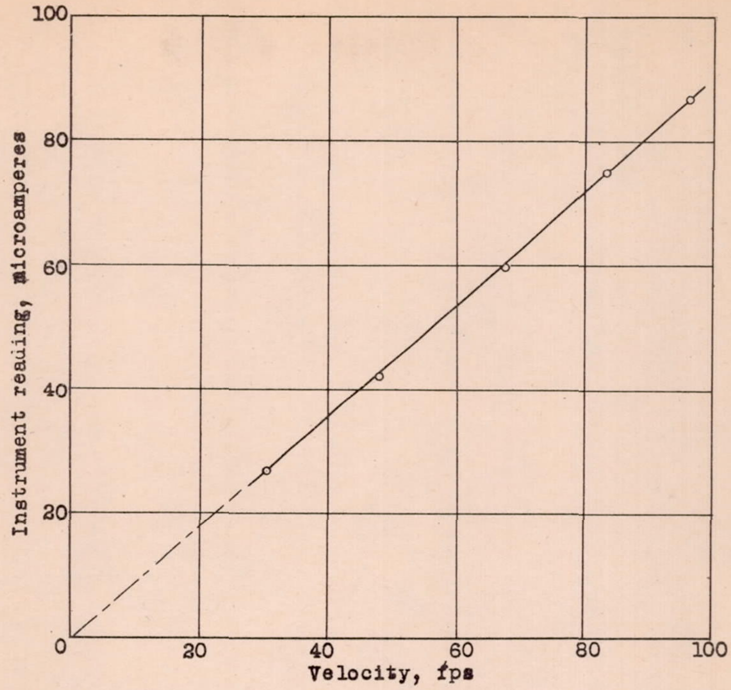


Figure 10.- Calibration curve for linear characteristic.

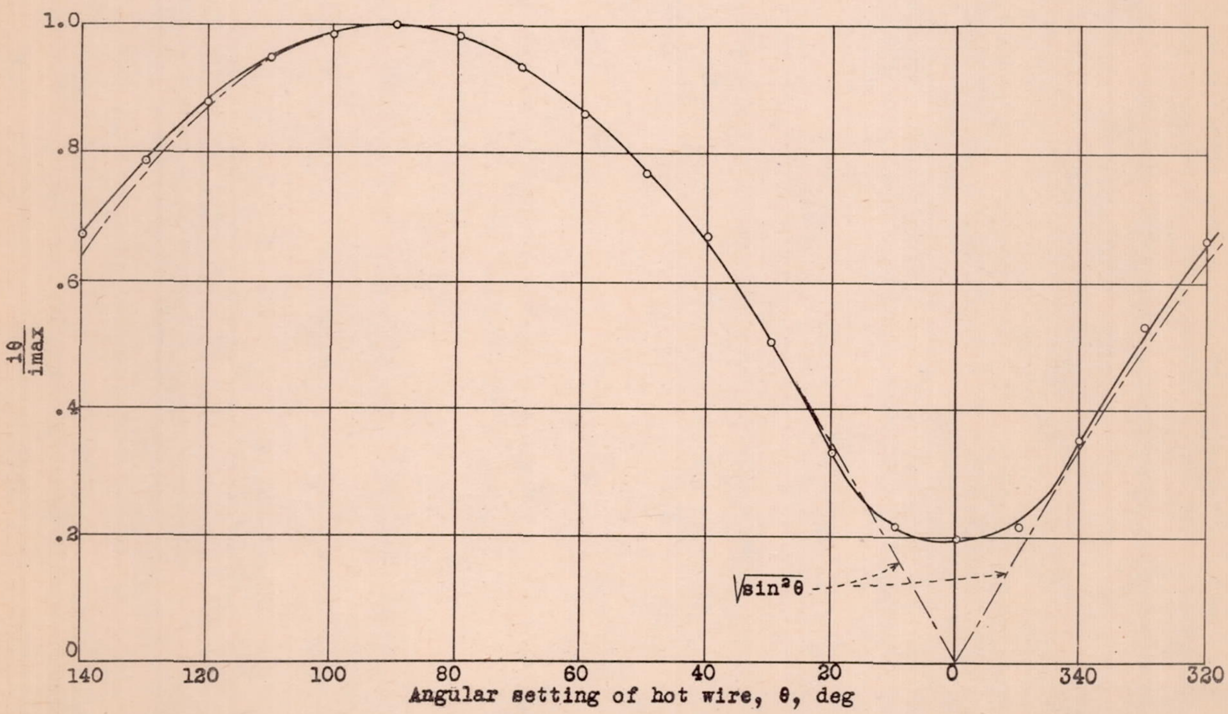


Figure 11.- Directional characteristics of the hot wire-circuit with linear readings.